Illuminating LMA-Dark solution and superlight sterile neutrinos by intermediate baseline reactor neutrino experiments

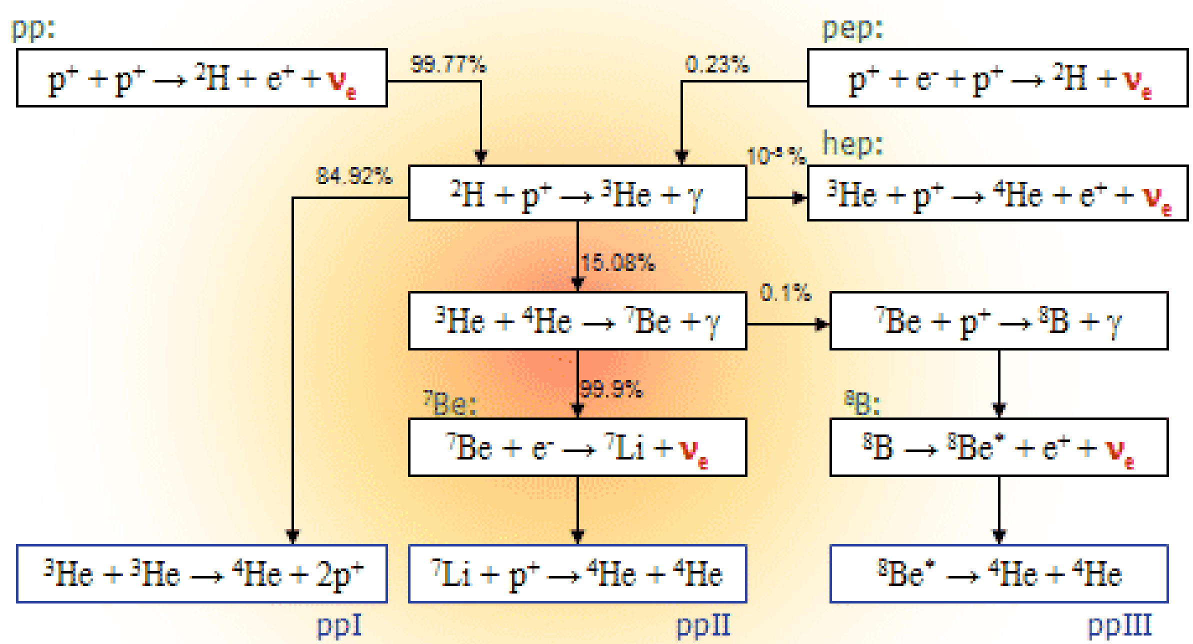
Yasaman Farzan
IPM

Outline of my talk

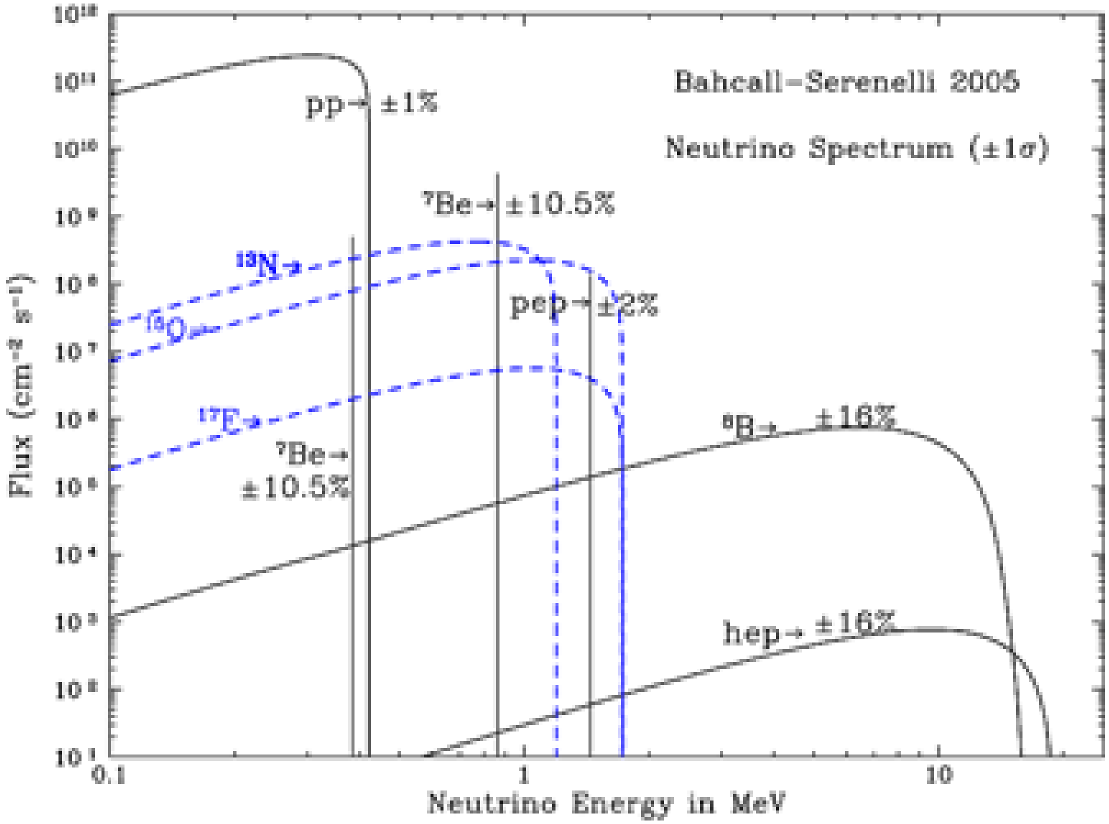
- Review: Solar Neutrino anomaly and MSW effect
- Some tension: suppression of low energy upturn
- Superlight Sterile Neutrino Scenario (SSNS)
- Testing SSNS via intermediate baseline reactor experiments: JUNO and RENO-50
- Summary
- Non-Standard Neutrino Interactions (NSI)
- LMA-Dark solution
- Testing LMA-Dark solution via intermediate baseline reactor experiments: JUNO and RENO-50
- Summary

Solar neutrinos

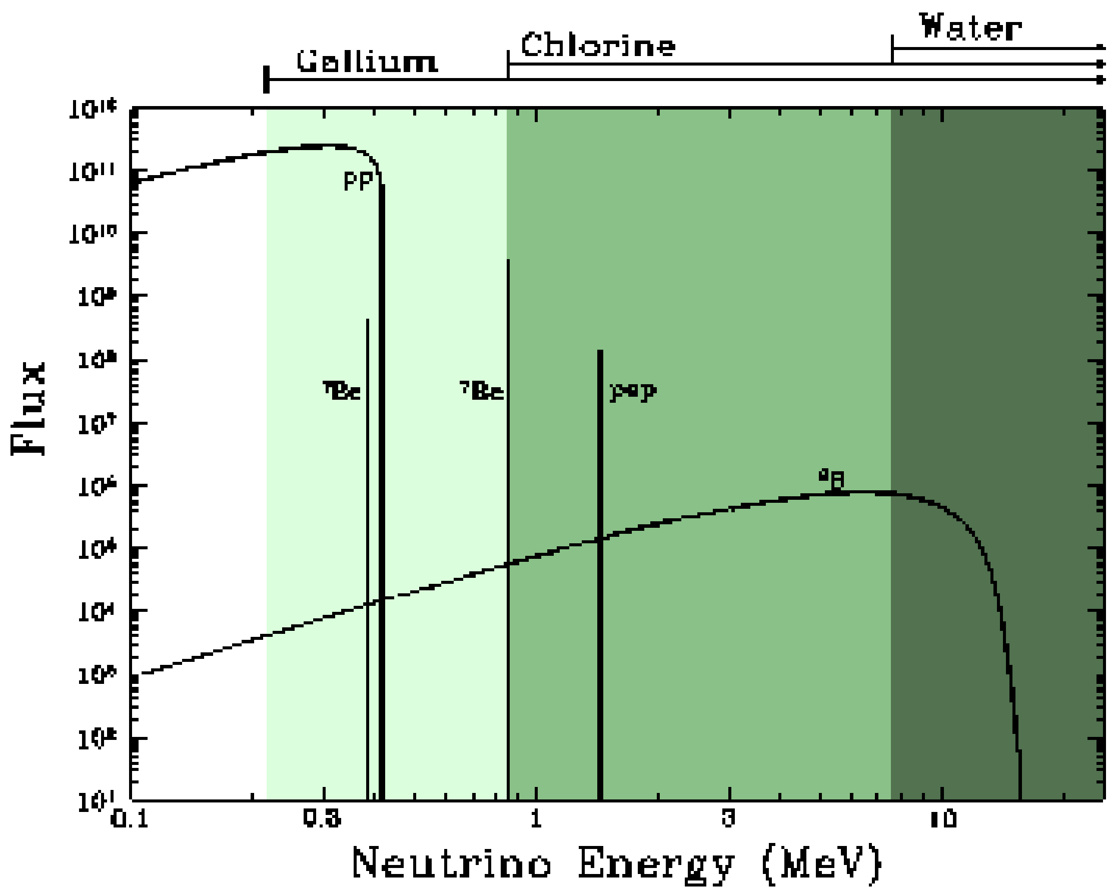
- Proton fusion: $4p \rightarrow He + 2e^{+} + 2\nu_e$



Solar Neutrino spectrum



Detection thresholds



Borexino threshold=0.25 MeV

Started data taking in 2007

Liquid scintillator

Homestake

- Gold mine in South Dakota-1960s-1994
- Raymond Davis and John Bahcall

$$\nu_e + \mathrm{Cl} \rightarrow e + \mathrm{Ar}$$

- Observed/predicted=1/3

Davis, Harmer and Hoffman, PRL (1968)

- Confirmed by Kamiokande, SAGE, GALLEX, Super-kamiokande and SNO

Solar Neutrino Anomaly

- SM: Lepton flavor conservation

↓ Solar neutrino anomaly

- Solution: Lepton flavor violation

PMNS mixing matrix

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

$U_{\alpha i}$ is a unitary matrix.

$$\sum_i U_{\alpha i} U^*_{\beta i} = \delta_{\alpha\beta} \qquad \sum_\alpha U_{\alpha i} U^*_{\alpha j} = \delta_{ij}$$

Propagation in matter

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix}=\mathcal{H}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix}$$

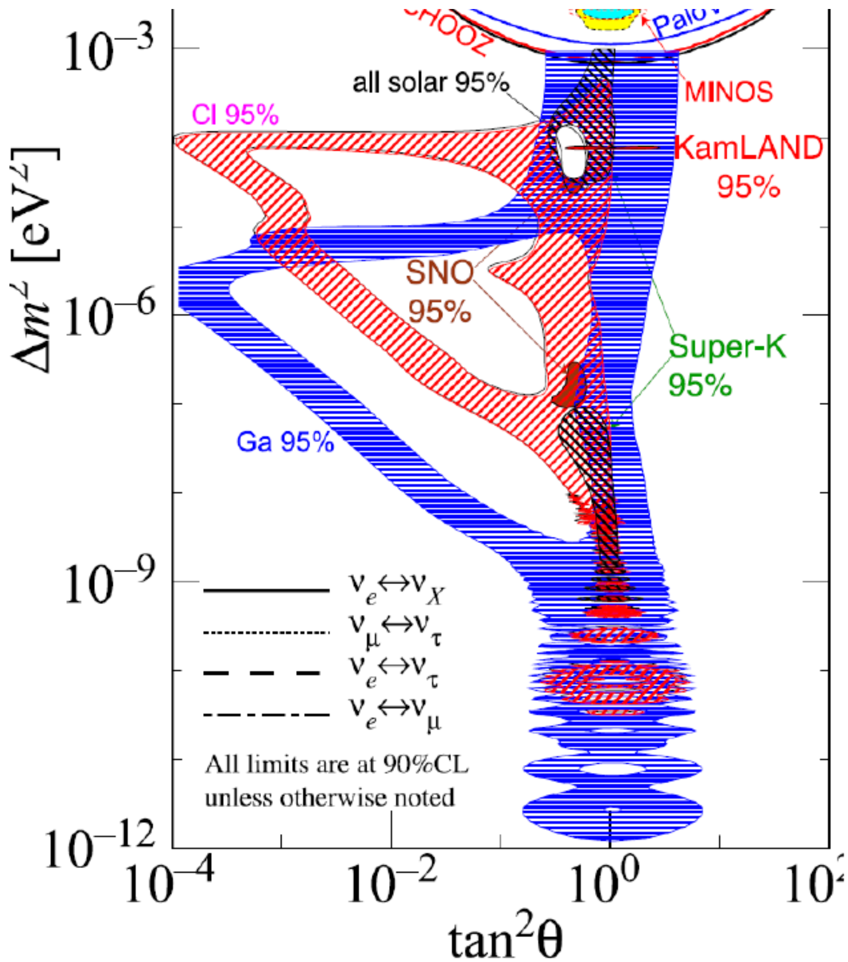
$$\mathcal{H}=\underbrace{\begin{pmatrix}\cos\theta & \sin\theta\\-\sin\theta & \cos\theta\end{pmatrix}\cdot\begin{pmatrix}0 & 0\\0 & \frac{\Delta m^2_{21}}{2E}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta & -\sin\theta\\\sin\theta & \cos\theta\end{pmatrix}}+\begin{pmatrix}V_e & 0\\0 & V_a\end{pmatrix}$$

Matter effect

$$V_e=\sqrt{2}G_F(n_e-n_n/2)\qquad V_a=-G_Fn_n/\sqrt{2}$$

KamLAND massacre!

~~Magnetic transition moment solution~~



LMA-solution

$$\theta_{12} = \left(33.57^{+0.77}_{0.675}\right)^\circ \qquad \Delta m^2_{21} = 7.45^{+0.19}_{-0.16}\ \mathrm{eV}^2$$

- Gonzalez-Garcia et al., JHEP 12 (2012) 123

NuFIT 1.2 (2013)

	Free Fluxes + RSBL		Huber Fluxes, no RSBL	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	$0.313^{+0.013}_{-0.012}$	$0.277 \to 0.355$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.37 \to 36.01$	$34.02^{+0.79}_{-0.76}$	$31.78 \to 36.55$
$\sin^2\theta_{23}$	$0.446^{+0.008}_{-0.008} \oplus 0.593^{+0.027}_{-0.043}$	$0.366 \to 0.663$	$0.444^{+0.037}_{-0.031} \oplus 0.592^{+0.028}_{-0.042}$	$0.361 \to 0.665$
$\theta_{23}/^\circ$	$41.9^{+0.5}_{-0.4} \oplus 50.3^{+1.6}_{-2.5}$	$37.2 \to 54.5$	$41.8^{+2.1}_{-1.8} \oplus 50.3^{+1.6}_{-2.5}$	$36.9 \to 54.6$
$\sin^2\theta_{13}$	$0.0231^{+0.0019}_{-0.0019}$	$0.0173 \to 0.0288$	$0.0244^{+0.0019}_{-0.0019}$	$0.0187 \to 0.0303$
$\theta_{13}/^\circ$	$8.73^{+0.35}_{-0.36}$	$7.56 \to 9.77$	$9.00^{+0.35}_{-0.36}$	$7.85 \to 10.02$
$\delta_{CP}/^\circ$	266^{+55}_{-63}	$0 \to 360$	270^{+77}_{-67}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	$7.50^{+0.18}_{-0.17}$	$7.03 \to 8.08$
$\frac{\Delta m^2_{31}}{10^{-3}\ \text{eV}^2}$ (N)	$+2.417^{+0.014}_{-0.014}$	$+2.247 \to +2.623$	$+2.429^{+0.055}_{-0.054}$	$+2.249 \to +2.639$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$ (I)	$-2.411^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	$-2.422^{+0.063}_{-0.061}$	$-2.614 \to -2.235$

http://www.nu-fit.org

Propagation in matter

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix}=\mathcal{H}\begin{pmatrix}|\nu_e\rangle\\|\nu_a\rangle\end{pmatrix}$$

$$\mathcal{H}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\cdot\begin{pmatrix}0 & 0\\ 0 & \frac{\Delta m_{21}^2}{2E}\end{pmatrix}\cdot\begin{pmatrix}\cos\theta & -\sin\theta\\ \sin\theta & \cos\theta\end{pmatrix}+\begin{pmatrix}V_e & 0\\ 0 & V_a\end{pmatrix}$$

Matter effect

$$V_e=\sqrt{2}G_F(n_e-n_n/2)\qquad V_a=-G_F n_n/\sqrt{2}$$

MSW effect

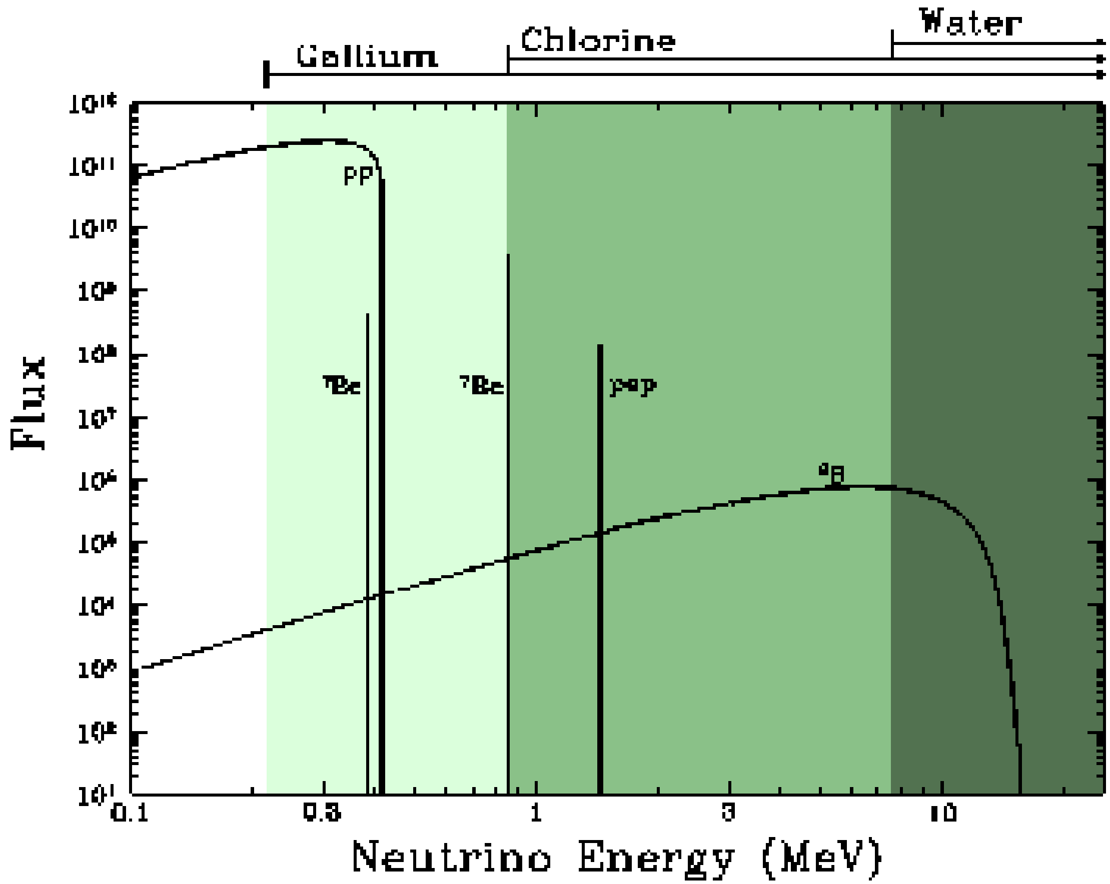
- Mikheyev Smirnov Wolfenstein effect

$$E \to 0: \quad \frac{\Delta m^2_{21}}{2E} \gg V_e - V_a \quad \text{vacuum oscillation limit}$$

$$E \to \infty: \quad \frac{\Delta m^2_{21}}{2E} \ll V_e - V_a \quad \text{matter effects limit}$$

For solar neutrinos transition takes place in 0.5-7 MeV.

Detection thresholds



Borexino threshold=0.25 MeV

Started data taking in 2007

Liquid scintillator

Does the Low energy solar data fit the MSW prediction?

- Be line measured by Borexino is in complete agreement.

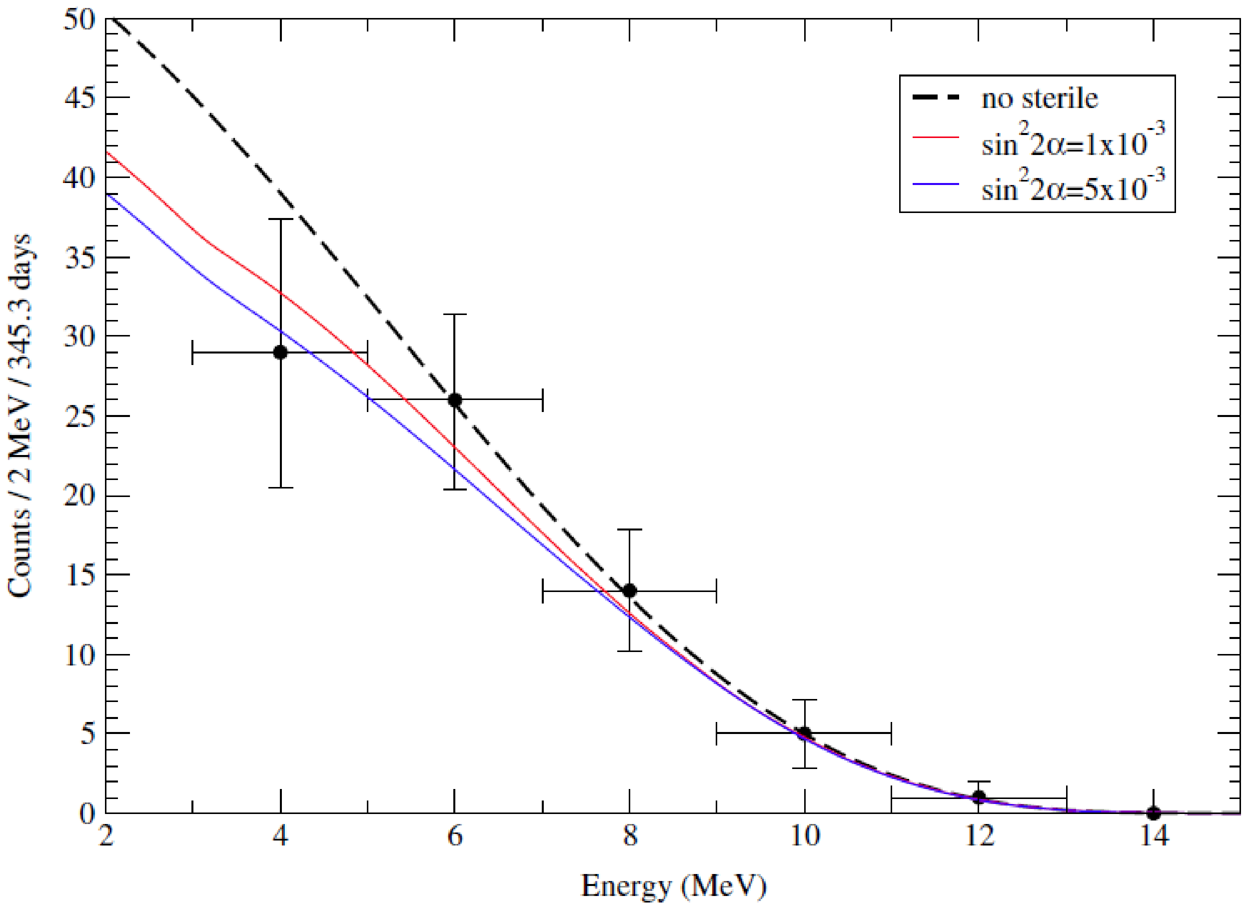
- But there is about 1-2 sigma deviation in data found by Homestake, Borexino (Boron spectrum), SNO-LETA, Super-Kamiokande I and III.

(For a review *see,* de Holanda and Smirnov, PRD83 (2011) 113011)

Boron Spectrum prediction has a 15 % uncertainty.

Absence of low energy upturn of the spectrum

PHYSICAL REVIEW D **83,** 113011 (2011)



^{8}B-neutrinos at Borexino

REDUCING UPTURN

- Superlight Sterile Neutrinos Scenario (SSNS):

De Holanda and Smirnov, PRD 83 (2011) 113611; PRD69 (2004) 113002.

- Non-standard interaction:

Miranda et al, JHEP 0610 (2006) 008; PRD 80 (2009) 105009.

SSNS

- Superlight sterile neutrinos Scenario (SSNS):
- Not to be confused with warm dark matter candidate or 1 eV sterile neutrino of LSND and MiniBooNE
- De Holanda and Smirnov, PRD 83 (2011) 113611:

$$\Delta m^2_{01} = (0.7 - 2) \times 10^{-5}\ \mathrm{eV}^2 \qquad \sin^2 2\alpha \sim 10^{-3}$$

SSNS formalism

$$\begin{pmatrix} \nu_s \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad U \equiv \begin{pmatrix} 1 & 0 \\ 0 & U_{PMNS} \end{pmatrix} \cdot U_S$$

$$U_S = \begin{pmatrix} \cos\alpha & \sin\alpha e^{i\delta_1} & 0 & 0 \\ -\sin\alpha e^{-i\delta_1} & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos\gamma & 0 & \sin\gamma & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\gamma & 0 & \cos\gamma & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \cos\beta & 0 & 0 & \sin\beta e^{i\delta_2} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\beta e^{-i\delta_2} & 0 & 0 & \cos\beta \end{pmatrix}$$

Atmospheric neutrinos for $\Delta m^2_{01} \sim 10^{-5}\ \mathrm{eV}^2$: $\sin^2\beta < 0.2.$

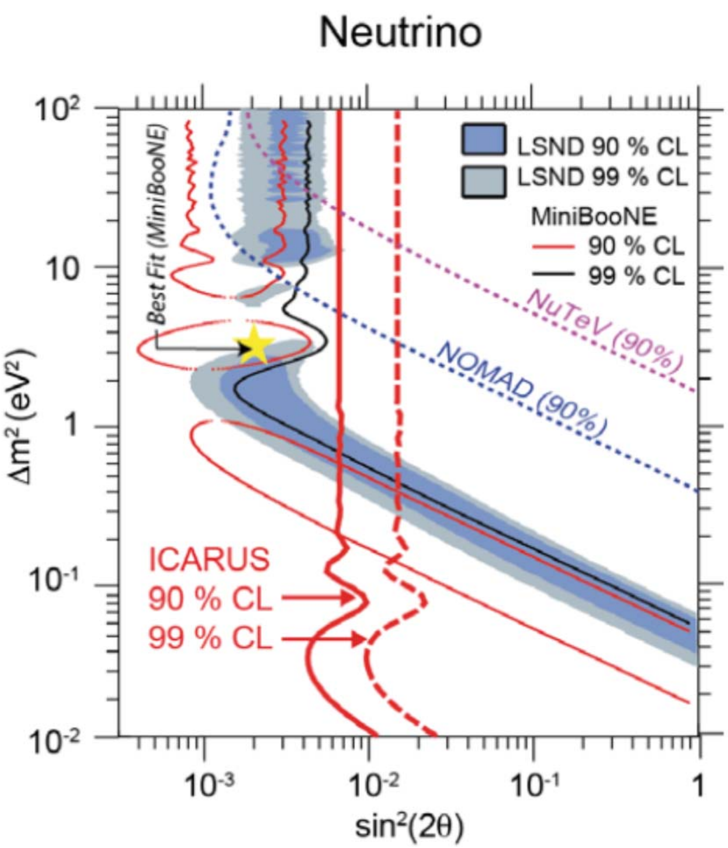
Cirelli et al, Nucl Phys B708 (2005) 215

Minos bound

$$\sin^2\beta \leq 0.2, \qquad (90\%\ \mathrm{C.L.}).$$

Adomson et al, PRD81 (210) 82004
arXiv:1104.3922

Icarus



A better bound from eletron neutrino appearance at ICARUS, Eur. Phys. J. C73 (20130 2599

arXiv:1307.3922

SSNS formalism

$$\begin{pmatrix}\nu_s\\ \nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \cdot \begin{pmatrix}\nu_0\\ \nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \qquad U \equiv \begin{pmatrix}1 & 0\\ 0 & U_{PMNS}\end{pmatrix} \cdot U_S$$

$$U_S = \begin{pmatrix}\cos\alpha & \sin\alpha e^{i\delta_1} & 0 & 0\\ -\sin\alpha e^{-i\delta_1} & \cos\alpha & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix} \cdot \begin{pmatrix}\cos\gamma & 0 & \sin\gamma & 0\\ 0 & 1 & 0 & 0\\ -\sin\gamma & 0 & \cos\gamma & 0\\ 0 & 0 & 0 & 1\end{pmatrix} \cdot \begin{pmatrix}\cos\beta & 0 & 0 & \sin\beta e^{i\delta_2}\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ -\sin\beta e^{-i\delta_2} & 0 & 0 & \cos\beta\end{pmatrix}$$

KamLAND and Solar data by 2005 for $\Delta m^2_{01} \sim 10^{-5}\ \mathrm{eV}^2$:

$$\sin^2\alpha < 0.1$$

Cirelli et al, Nucl Phys B708 (2005) 215

Extra relativistic degrees of freedom

$$\Delta N_{eff} \ll 1$$

- Mirizzi et al, PLB726 (2013) 8-14

$$\sin^2\alpha,\ \sin^2\beta,\ \sin^2\gamma < \text{few} \times 10^{-2}$$

- However, …..

Wyman et al, arXiv:1307.7715, Archidiacono et al, arXiv:1307.0637

Effect on solar data

- For $\Delta m^2_{01} = (0.7 - 2) \times 10^{-5}\ \mathrm{eV}^2 \quad \sin^2 2\alpha \sim 10^{-3}$
- Electron neutrino to sterile neutrino conversion
- Dip in survival probability for E=0.5-7 MeV
- Suppression of upturn at lower range energies

Testing SSN

- KamLAND solar, SNO+, … (De Holanda and Smirnov, PRD 83 (2011) 113611).

- Can we test via reactor experiments?

Pouya Bakhti and Y.F., JHEP 10 (2013) 200.

Medium Baseline reactor experiments

- DAYA BAY in CHINA → JUNO
- RENO in South Korea → RENO-50

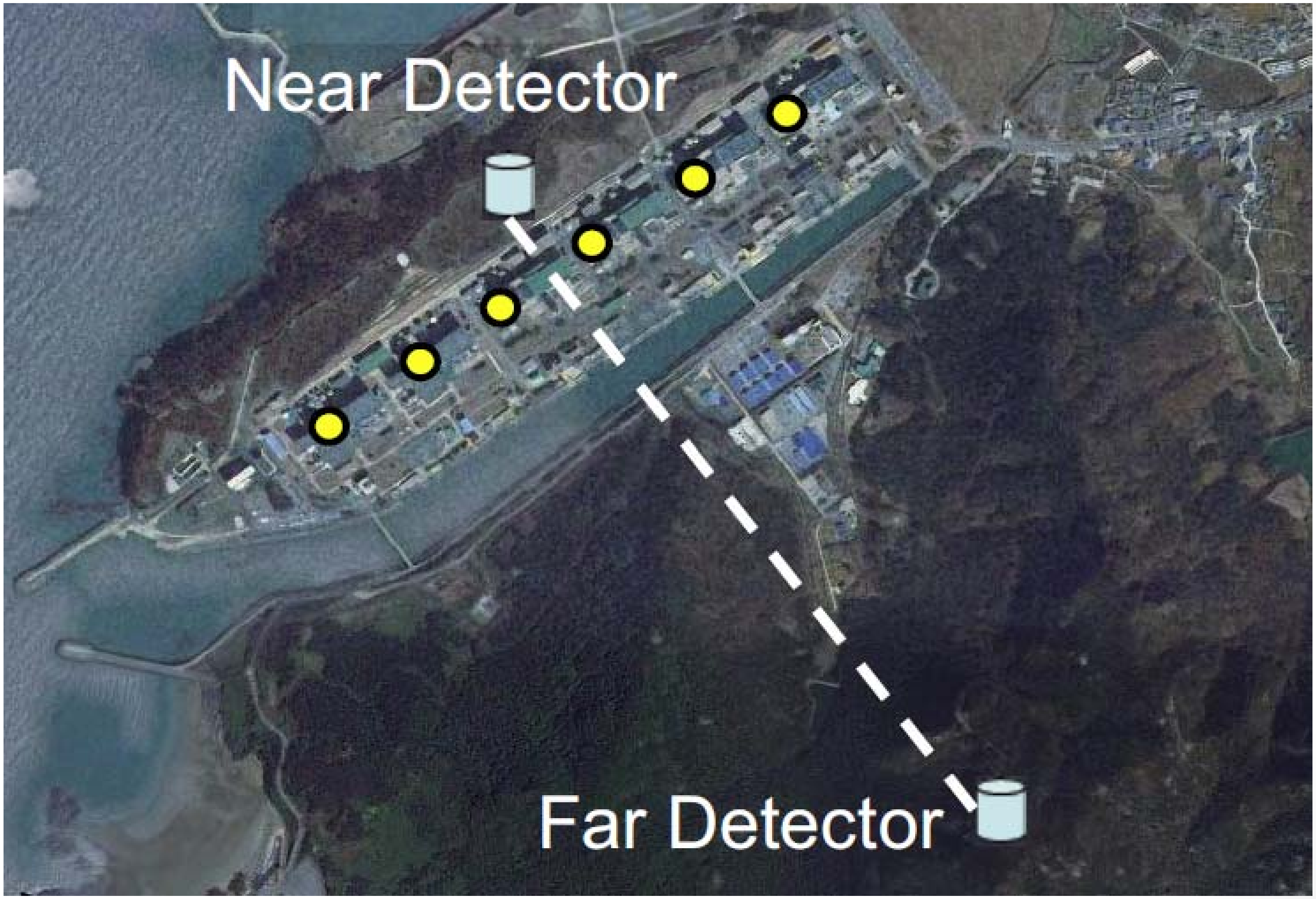
Ready for data taking in 2020.

- Baseline ~ 50 km

$$\frac{\Delta m^2_{01} L}{2E_\nu} \sim 0.4 \frac{\Delta m^2_{01}}{10^{-5}\ \mathrm{eV}^2} \frac{L}{50\ \mathrm{km}} \frac{3\ \mathrm{MeV}}{E_\nu}$$

- Main goal determination of $\mathrm{sgn}(\Delta m^2_{31})$

RENO-50 in South Korea



Daya Bay and Juno

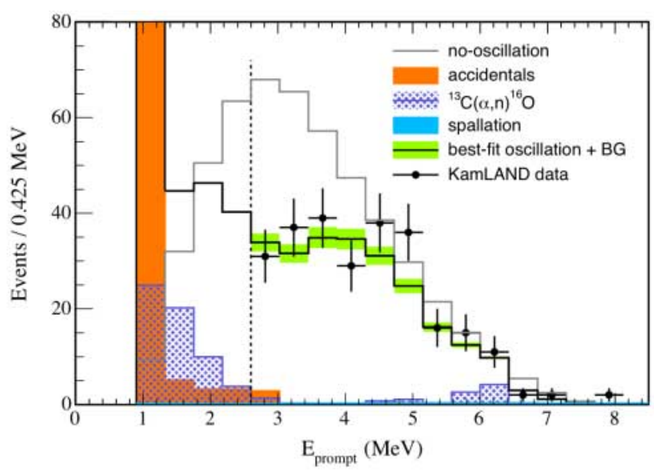
Detector characteristics

Liquid Scintillator

- Reno-50: 18 kton, 16.4 GW
- JUNO: 20 kton, 36 GW

$$\text{Energy resolution} \sim 3\% \sqrt{\frac{E_\nu}{\text{MeV}}}$$

- 62 energy bins between 1.8-8MeV
-
-



Oscillation in SSNS

- For reactor neutrinos

$$V_{eff} \sim G_F n_e \sim G_F n_n \ll \Delta m_{01}^2/E_\nu < \Delta m_{21}^2/E_\nu \ll |\Delta m_{31}^2/E_\nu|.$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left| M_0 e^{i\Delta_0} + M_1 e^{i\Delta_1} + M_2 e^{i\Delta_2} + M_3 e^{i\Delta_3} \right|^2$$

$$\Delta_i = m_i^2 L/2E_\nu$$

$$\begin{aligned}
M_0 &= |\cos\beta(-e^{-i\delta_1}\cos\gamma\cos\theta_{12}\cos\theta_{13}\sin\alpha - \cos\theta_{13}\sin\gamma\sin\theta_{12}) - e^{-i(\delta_D+\delta_2)}\sin\beta\sin\theta_{13}|^2, \\
M_1 &= |\cos\alpha\cos\theta_{12}\cos\theta_{13}|^2 \\
M_2 &= |-e^{-i\delta_1}\cos\theta_{12}\cos\theta_{13}\sin\alpha\sin\gamma + \cos\gamma\cos\theta_{13}\sin\theta_{12}|^2 \\
M_3 &= |\sin\beta(-e^{-i\delta_1}\cos\gamma\cos\theta_{12}\cos\theta_{13}\sin\alpha - \cos\theta_{13}\sin\gamma\sin\theta_{12}) + e^{-i(\delta_D+\delta_2)}\cos\beta\sin\theta_{13}|^2.
\end{aligned}$$

GloBES

Authors:
GLoBES is maintained by Patrick Huber
Joachim Kopp
Manfred Lindner
Walter Winter

http://www.mpi-hd.mpg.de/personalhomes/globes/index.html

Huber, Lindner and Winter, **Comput.Phys.Commun. 167 (2005) 195**

Huber et al, **Comput.Phys.Commun. 177 (2007) 432-438**

Backgrounds

(i) accidental background;

(ii) $^{13}C(\alpha, n)^{16}O$ background

(iii) Geoneutrino background.

- Kettell et al, arXiv:1307.7419; Ciuffoli et al., arXiv:1302.0624.

Uncertainties

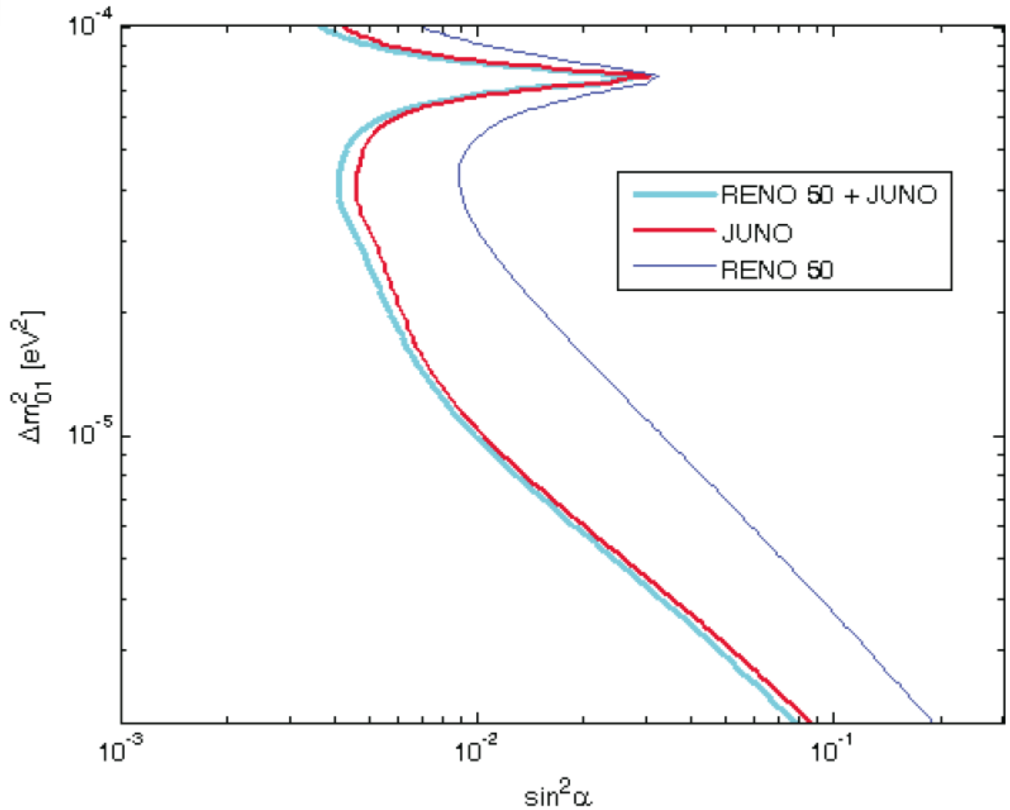
- We use pull-method to treat uncertainties in neutrino parameters and flux.

- 3 % flux uncertainty for JUNO

- 0.3 % flux uncertainty for RENO-50

- Gonzalez-Garcia et al, JHEP 12 (2012) 123 (nu-fit.org)

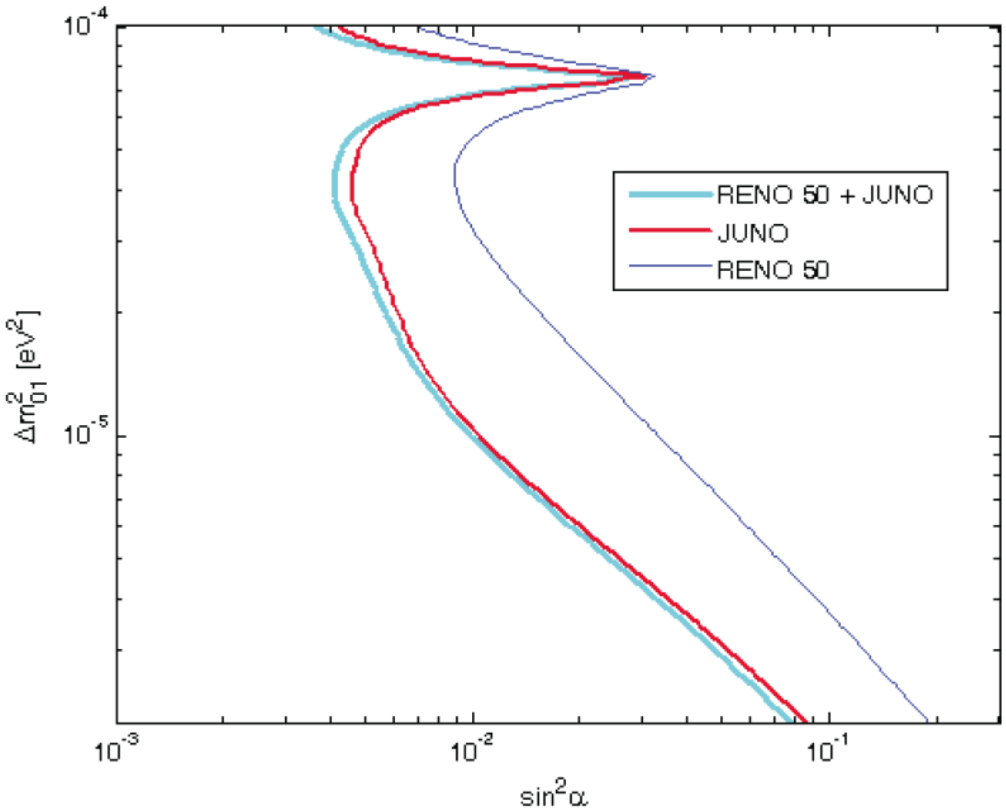
$$\theta_{12}\ ,\theta_{23}\ ,\Delta m^2_{31}\ ,\Delta m^2_{21}$$



The 95% C.L. upper bound on $\sin^2\alpha$ versus Δm^2_{01}.

$$\alpha = \beta = \gamma = 0$$

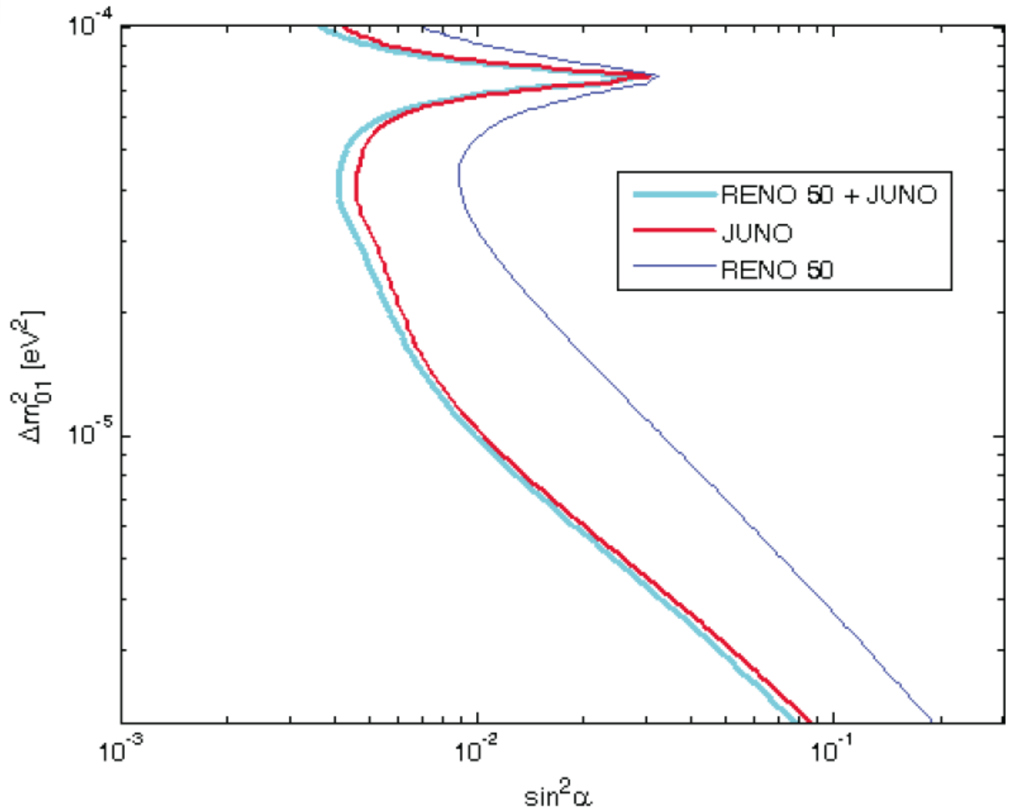
- Five years of data taking



Case I, $\sin\beta = \sin\gamma = 0$ *and* $\alpha \neq 0$:

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\cos^2\theta_{13}\cos^2\theta_{12}\sin^2\alpha e^{i\Delta_0} + \cos^2\alpha\cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}e^{i\Delta_2} + \sin^2\theta_{13}e^{i\Delta_3}\right|^2$$

As expected in the $\Delta m^2_{01} \to 0$ limit, the sensitivity to α is lost.



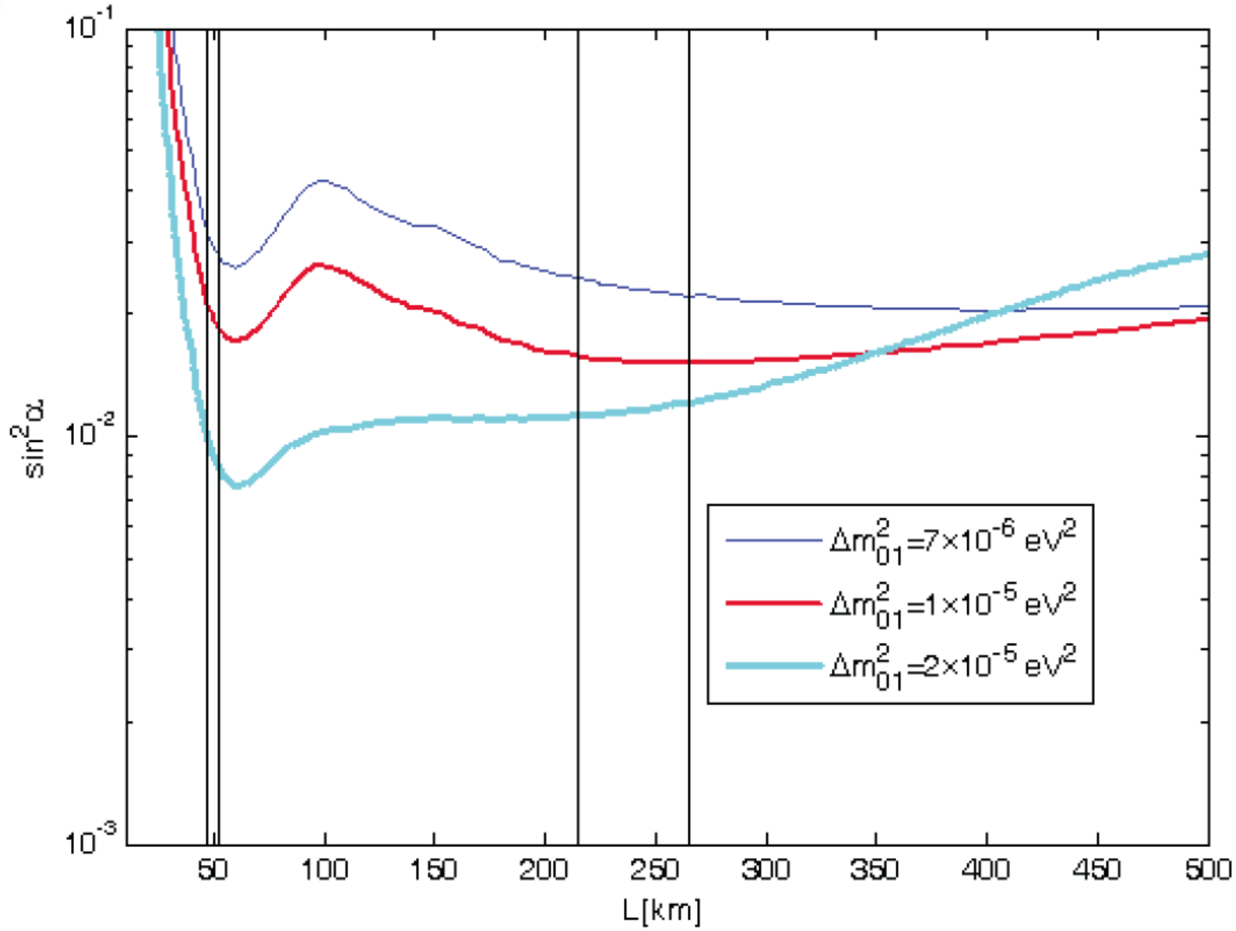
$$\Delta_0 \rightarrow \Delta_2,$$

$$\Delta m^2_{01} \rightarrow \Delta m^2_{21}$$

$$Case\ I,\ \sin\beta = \sin\gamma = 0\ \ and\ \ \alpha \neq 0:$$

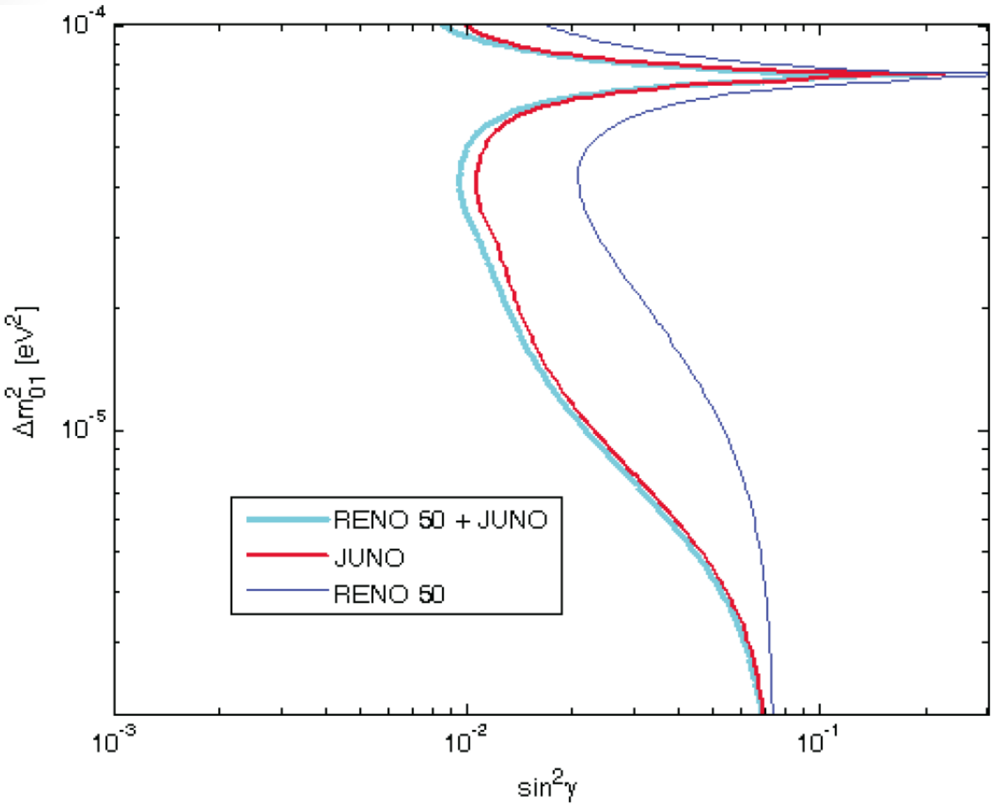
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \left|\cos^2\theta_{13}\cos^2\theta_{12}\sin^2\alpha e^{i\Delta_0} + \cos^2\alpha\cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}e^{i\Delta_2} + \sin^2\theta_{13}e^{i\Delta_3}\right|^2$$

- Uncertainty in θ_{12}: $\sin^2\alpha < \delta\sin^2\theta_{12}/\cos^2\theta_{12}$.

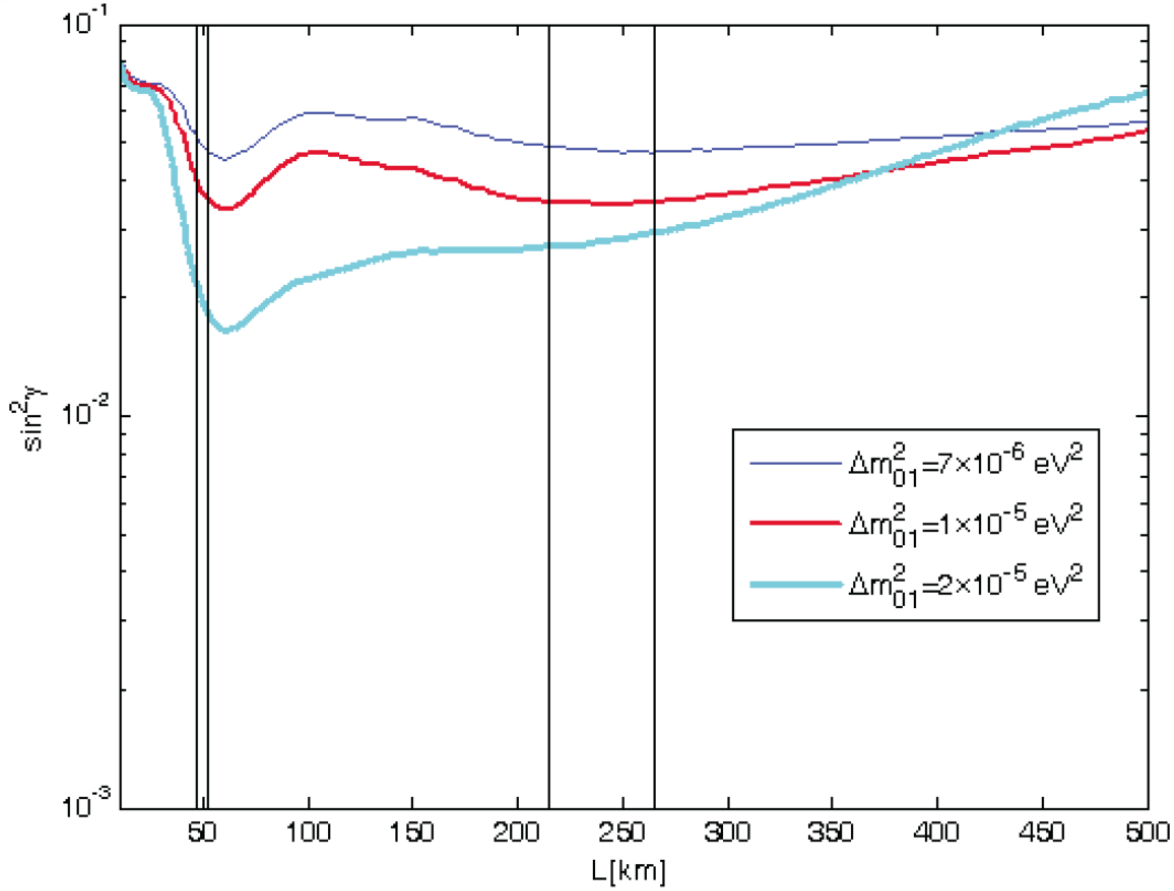


The 95% C.L. upper bound on $\sin^2\alpha$ versus the baseline

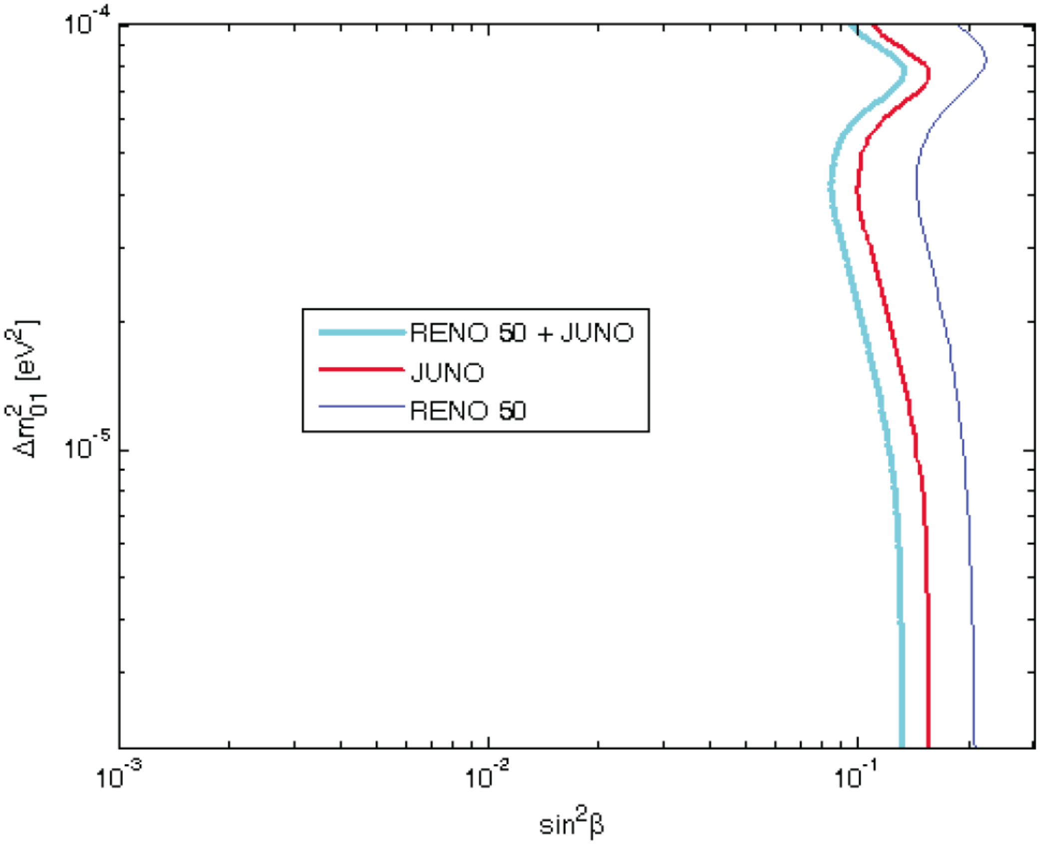
Five years of data taking with a 20 kton detector and 36 GW reactor source



$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\cos^2\theta_{13}\sin^2\theta_{12}\sin^2\gamma e^{i\Delta_0} + \cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}\cos^2\gamma e^{i\Delta_2} + \sin^2\theta_{13}e^{i\Delta_3}\right|^2$$



The 95% C.L. upper bound on $\sin^2 \gamma$ versus the baseline.



Case III, $\sin\alpha = \sin\gamma = 0$ *and* $\beta \neq 0$: In this limit,

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left|\sin^2\theta_{13}\sin^2\beta e^{i\Delta_0} + \cos^2\theta_{13}\cos^2\theta_{12}e^{i\Delta_1} + \cos^2\theta_{13}\sin^2\theta_{12}e^{i\Delta_2} + \sin^2\theta_{13}\cos^2\beta e^{i\Delta_3}\right|^2$$

$$\sin^2\theta_{13} \ll 1$$

SSNS

- Superlight sterile neutrinos Scenario (SSNS):
- De Holanda and Smirnov, PRD 83 (2011) 113611.

- Parameter range to cure upturn of low energy solar neutrinos:

$$\Delta m_{01}^2 = (0.7 - 2) \times 10^{-5}\ \mathrm{eV}^2 \qquad \sin^2 2\alpha \sim 10^{-3}$$

To probe such small values of mixing about 20 years of data taking is required.

How to improve

- The results are not too sensitive to background, energy resolution, normalization uncertainty of flux and etc
- Accumulation of flux from various reactors are useful
- Main limitation: statistics
- Going to Bigger detector and longer data collecting time smaller values of mixing can be probed.

Conclusion

- The medium baseline reactor experiments can (in principle) probe SSNS

Non-standard Interaction

- Within SM, neutral current interaction are flavor-diagonal and universal.

- But, going to beyond SM

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma_\mu P\ f)$$

Examples: Grand unification, various seesaw models, extra U(1), left-right symmetric modeld, etc

T.Ohlsson, Rept. Prog. Phys 76 (2013) 044201

NSI

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon^{fP}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma_\mu P\ f)$$

f is the matter field (u, d or e).

P is the chirality projection matrix

$\epsilon^{fP}_{\alpha\beta}$ is a dimensionless matrix

Relevant for neutrino oscillation

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fP} (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta)(\bar{f}\gamma_\mu P\ f)$$

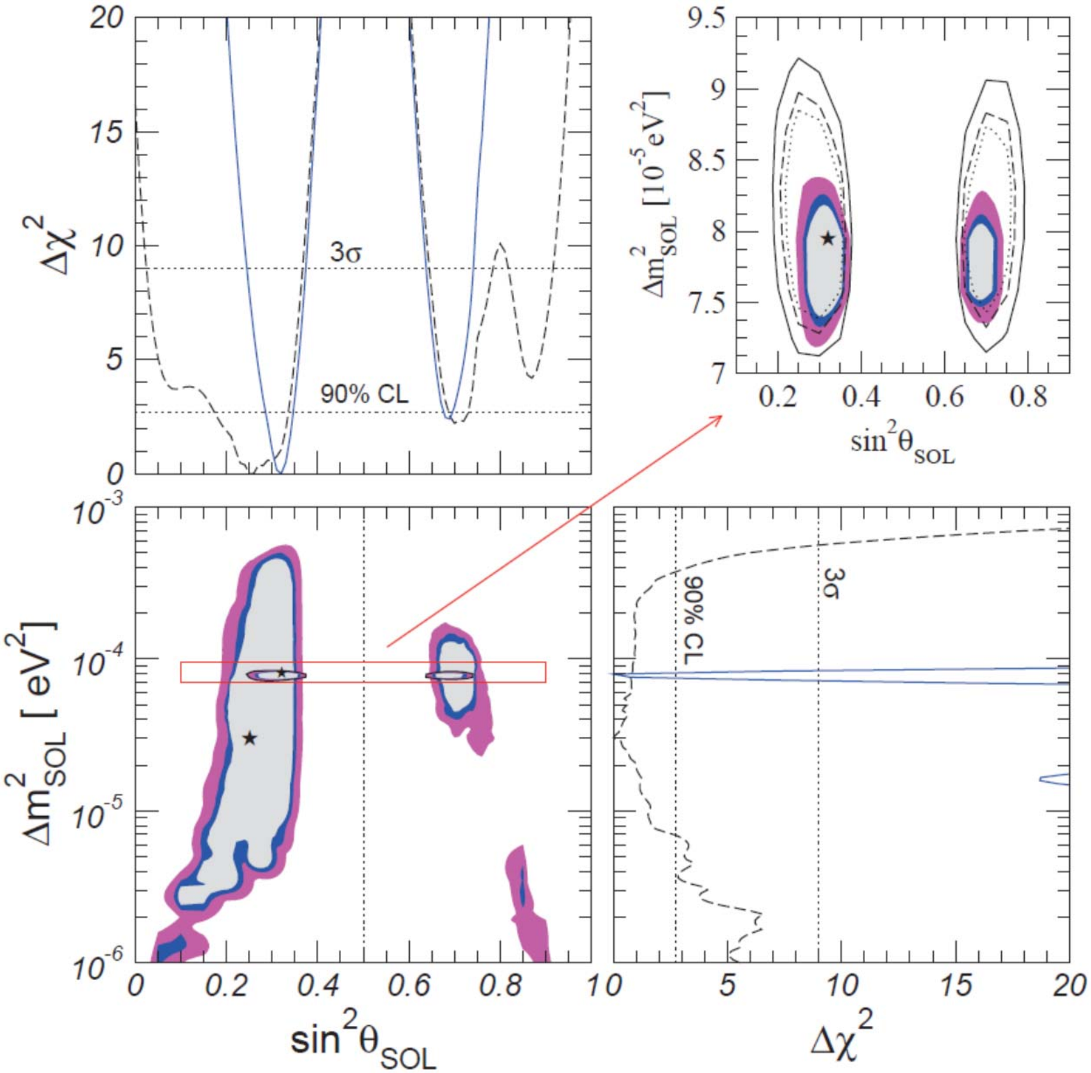
$$\epsilon_{\alpha\beta}^{f} \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}.$$

LMA-Dark solution

- For $$|\epsilon^f_{ee} - \epsilon^f_{\mu\mu}|, |\epsilon^f_{ee} - \epsilon^f_{\tau\tau}| \neq 0$$

- Another solution with $$\cos(2\theta_{12}) < 0$$

O. G. Miranda, M. A. Tortola and J. W. F. Valle, JHEP **0610** (2006) 008 [hep-ph/0406280]; O. G. Miranda, M. A. Tortola and J. W. F. Valle, AIP Conf. Proc. **917** (2007) 100; F. J. Escrihuela, O. G. Miranda, M. A. Tortola and J. W. F. Valle, Phys. Rev. D **80** (2009) 105009 [Erratum-ibid. D **80** (2009) 129908] [arXiv:0907.2630 [hep-ph]]; *see also,* A. Friedland and I. M. Shoemaker, arXiv:1207.6642 [hep-ph].



- Miranda et al., JHEP 0610 (2006) 008

Has LMA-dark solution survives?

- Solution survives the test of all the neutrino

Gonzalez-Garcia and Maltoni, JHEP 1309 (2013) 152

3 sigma range

Standard Matter Potential	Generalized Matter Potential
$\sin^2\theta_{12} \in [0.27, 0.35]$,	$\sin^2\theta_{12} \in [0.26, 0.35] \oplus [0.65, 0.75]$,
$\sin^2\theta_{23} \in [0.36, 0.67]$,	$\sin^2\theta_{23} \in [0.34, 0.67]$,
$\sin^2\theta_{13} \in [0.016, 0.030]$,	$\sin^2\theta_{13} \in [0.016, 0.030]$,
$\Delta m^2_{21} \in [6.87, 8.03] \times 10^{-5}$ eV^2,	$\Delta m^2_{21} \in [6.86, 8.10] \times 10^{-5}$ eV^2,
$\lvert\Delta m^2_{31}\rvert \in [2.20, 2.58] \times 10^{-3}$ eV^2,	$\lvert\Delta m^2_{31}\rvert \in [2.20, 2.65] \times 10^{-3}$ eV^2.

		90% CL		3σ	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\,[-1.19, -0.81]$	$[-0.09, +0.71]$	$\oplus\,[-1.40, -0.68]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$	$[-0.03, +0.20]$	$[-0.19, +0.20]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$	$[-0.40, +0.30]$	$[-0.40, +0.40]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^u_D	-0.140	$[-0.24, -0.01]$	$\oplus\,[+0.40, +0.58]$	$[-0.34, +0.04]$	$\oplus\,[+0.34, +0.67]$
ε^u_N	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$	$[-0.29, +0.21]$	$[-0.29, +0.21]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\,[-1.17, -1.03]$	$[-0.10, +0.71]$	$\oplus\,[-1.44, -0.87]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$	$[-0.03, +0.19]$	$[-0.16, +0.19]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$	$[-0.38, +0.29]$	$[-0.38, +0.35]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^d_D	-0.145	$[-0.25, -0.02]$	$\oplus\,[+0.49, +0.57]$	$[-0.34, +0.05]$	$\oplus\,[+0.42, +0.70]$
ε^d_N	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$	$[-0.28, +0.21]$	$[-0.28, +0.21]$

LMA-Dark

- LMA-Dark solution fits the solar data slightly better as it suppresses the upturn of the spectrum at low energy

Other bounds

- Invisible Z-decay (loop level)
- Neutrino scattering off matter
- Ohlsson, Rept Prog Phys 76 (2013) 44201

Other bounds

- Invisible Z-decay (loop level)
- Neutrino scattering off matter
- Ohlsson, Rept Prog Phys 76 (2013) 44201
- The bound from CHARM scattering experiment combined with NuTeV rules out a part of parameter space for LMA-Dark.

$$(i.e.,\ 0.9 < |\epsilon^d_{ee} - \epsilon^d_{\mu\mu}| < 0.8 \text{ at } 90\ \%\ \text{C.L.})$$

Davidson, Pena-Garay, Rius and Santamaria, JHEP 0303 (2003) 011.

Medium Baseline reactor experiments

- DAYA BAY in CHINA → JUNO
- RENO in South Korea → RENO-50

Ready for data taking in 2020.

- Baseline ~ 50 km

$$\frac{\Delta m^2_{01} L}{2E_\nu} \sim 0.4 \frac{\Delta m^2_{01}}{10^{-5}\ \mathrm{eV}^2} \frac{L}{50\ \mathrm{km}} \frac{3\ \mathrm{MeV}}{E_\nu}$$

- Main goal determination of $\mathrm{sgn}(\Delta m^2_{31})$

Charged current NSI

- Charged current NSI

$$(\bar{d}\gamma^{\mu}P\ u)(\bar{e}\gamma_{\mu}L\nu_{\mu(\tau)})$$

Affects neutrino production and detection

- Neutral current NSI

$$(\bar{\nu}_{\alpha}\gamma^{\mu}L\nu_{\beta})(\bar{f}\gamma_{\mu}P\ f)$$

Affects neutrino propagation through matter effects

Charged current NSI at JUNO

$$|\hat{\nu}^{\rm s}_\alpha\rangle = \frac{1}{N^{\rm s}_\alpha}\left(|\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^{\rm s}_{\alpha\beta}|\nu_\beta\rangle\right)$$

$$\langle\hat{\nu}^{\rm d}_\beta| = \frac{1}{N^{\rm d}_\beta}\left(\langle\nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon^{\rm d}_{\alpha\beta}\langle\nu_\alpha|\right)$$

Khan et al, PRD 88 (2013) 113006
Ohlsson, Zhang and Zhou, PLB 728 (2014) 148

Neutral current NSI at reactor neutrino experiments

$$\Delta m^2_{21}/E_\nu \gg \sqrt{2}G_F N_e$$

- Small matter effects

- Little sensitivity to neutral current NSI

Our suggestion to test LMA-Dark

- Pouya Bakhti and Y.F., 1403.0744

- Determining $\cos 2\theta_{12}$

Survival probability without matter effects

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left| |U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}} \right|^2 = \left| c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}} \right|^2 =$$

$$c_{13}^4 (1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta_{21}}{2}) + s_{13}^4 + 2 s_{13}^2 c_{13}^2 [\cos\Delta_{31} (c_{12}^2 + s_{12}^2 \cos\Delta_{21}) + s_{12}^2 \sin\Delta_{31} \sin\Delta_{21}]$$

where $\Delta_{ij} = \Delta m_{ij}^2 L/(2E_\nu)$ in which L is the baseline.

Observation

- A reactor neutrino set-up that is sensitive to hierarchy should also distinguish between solution

$$\text{with } \theta_{12} > \pi/4 \text{ and } \theta_{12} < \pi/4$$

GloBES

Authors:
GLoBES is maintained by Patrick Huber
Joachim Kopp
Manfred Lindner
Walter Winter

http://www.mpi-hd.mpg.de/personalhomes/globes/index.html

Huber, Lindner and Winter, **Comput.Phys.Commun. 167 (2005) 195**

Huber et al, **Comput.Phys.Commun. 177 (2007) 432-438**

Characteristics of JUNO and RENO-50

- The same as before except that we added

background caused by ^9Li from cosmic muon interaction

- Grassi, Evslin Giuffoli and Zhang, 1401.7796

- 10000 and 5000 fake neutrinos from Li at JUNO and RENO-50

Energy bins

- Energy range between 1.8 to 8 MeV to 350 bins 0f 17.7 keV

- Good energy resolution is required

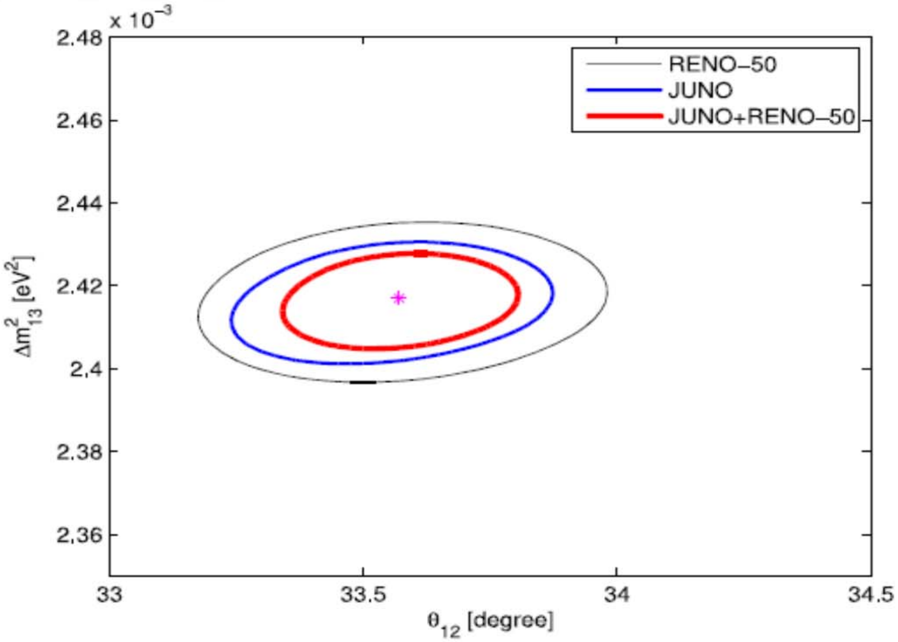
$$\frac{\delta E_\nu}{E_\nu} \simeq 3\% \times (\frac{E_\nu}{\mathrm{MeV}})^{1/2}.$$

Results

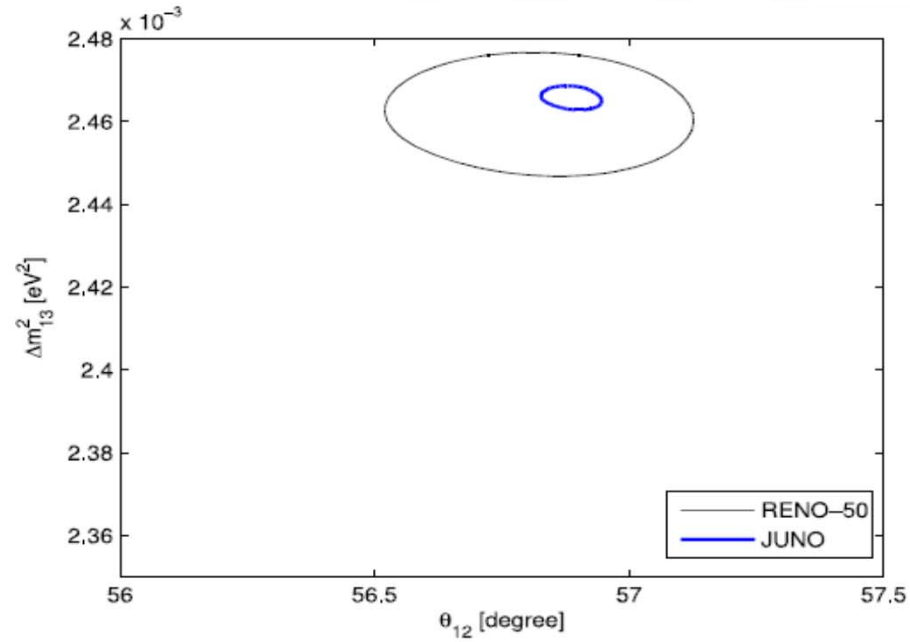
- After 5 years of data taking by JUNO and RENO-50

$$\Delta m^2_{21} = (7.45 \pm 0.45) \times 10^{-5}\ \text{eV}^2$$

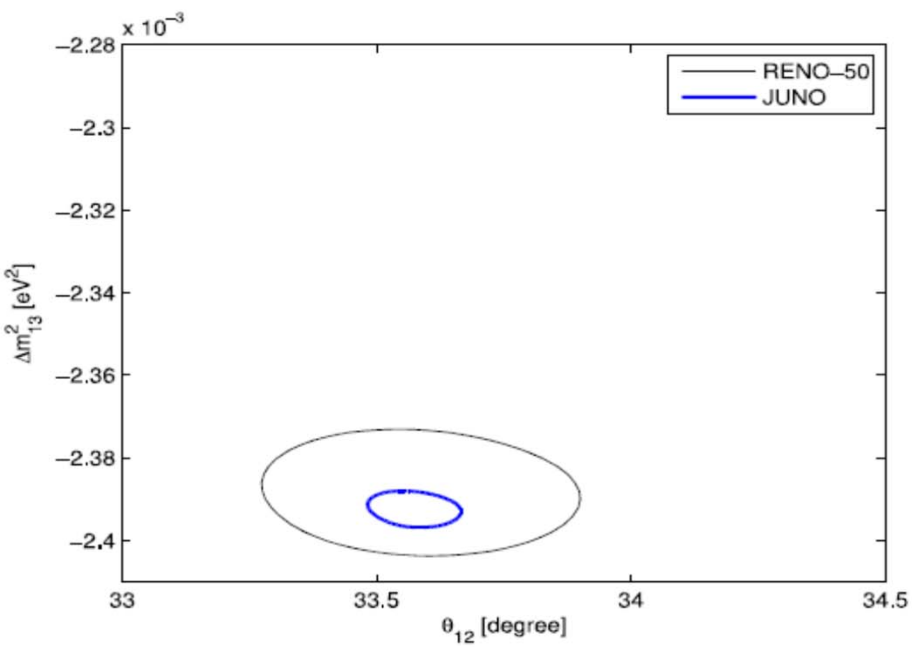
$$\theta_{13} = (8.75 \pm 0.5)^\circ$$


x 10^-3
RENO–50
JUNO
JUNO+RENO–50
Δm^2_{13} [eV^2]
θ_{12} [degree]
2,48
2,46
2,44
2,42
2,4
2,38
2,36
33
33.5
34
34.5

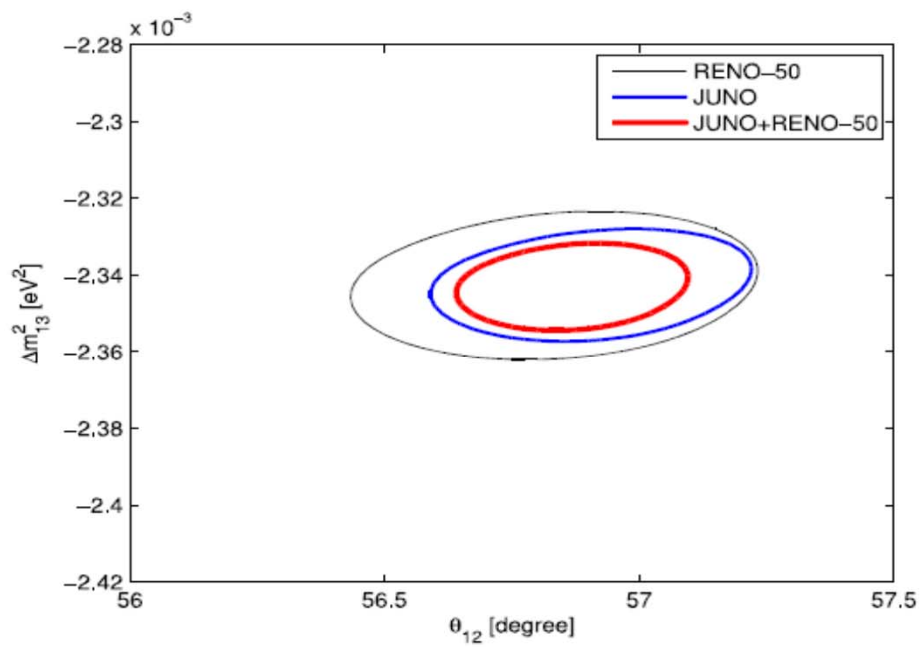
(a)


x 10^-3
RENO–50
JUNO
Δm^2_{13} [eV^2]
θ_{12} [degree]
2,48
2,46
2,44
2,42
2,4
2,38
2,36
56
56.5
57
57.5

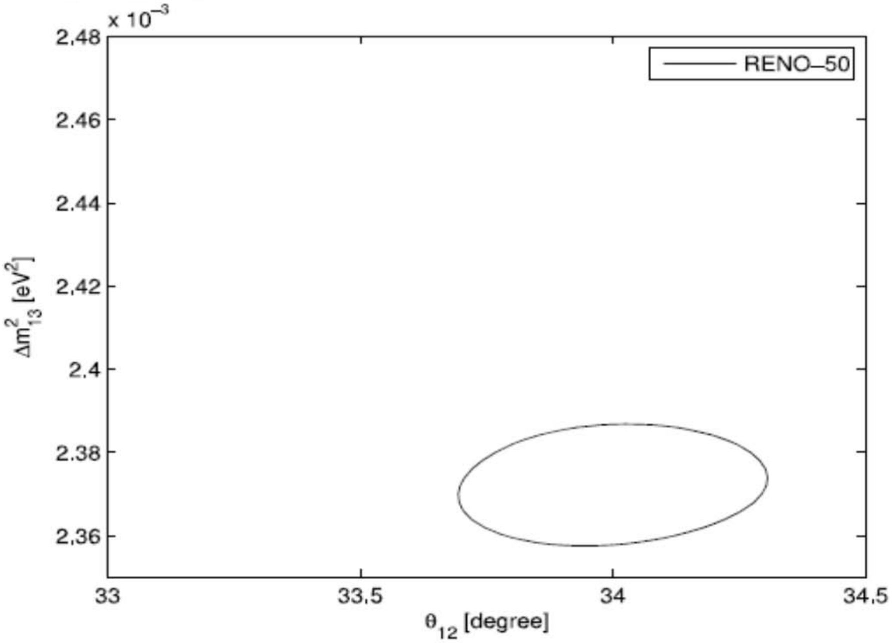
(b)


x 10^-3
RENO–50
JUNO
Δm^2_{13} [eV^2]
θ_{12} [degree]
−2,28
−2,3
−2,32
−2,34
−2,36
−2,38
−2,4
33
33.5
34
34.5

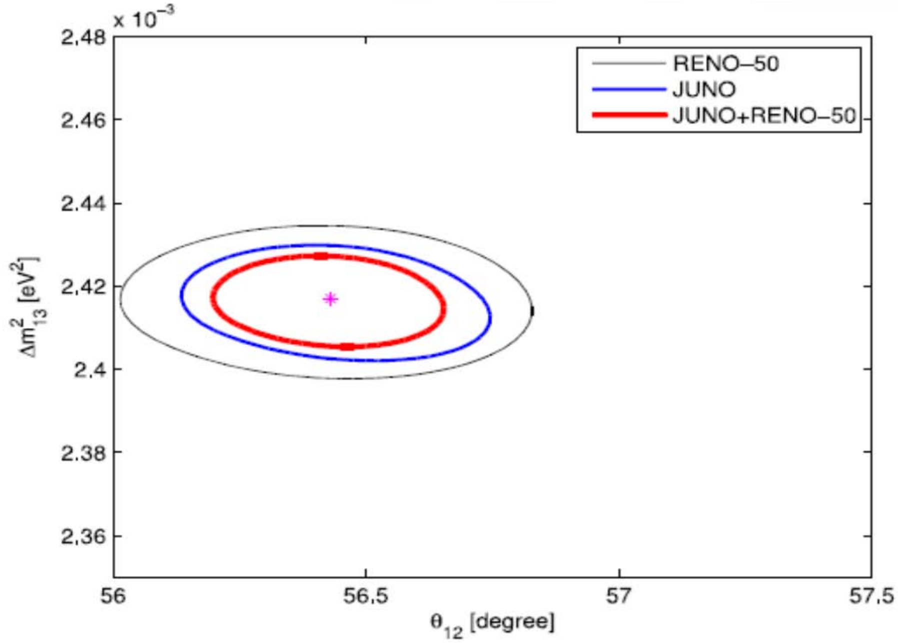
(c)


x 10^-3
RENO–50
JUNO
JUNO+RENO–50
Δm^2_{13} [eV^2]
θ_{12} [degree]
−2,28
−2,3
−2,32
−2,34
−2,36
−2,38
−2,4
−2,42
56
56.5
57
57.5

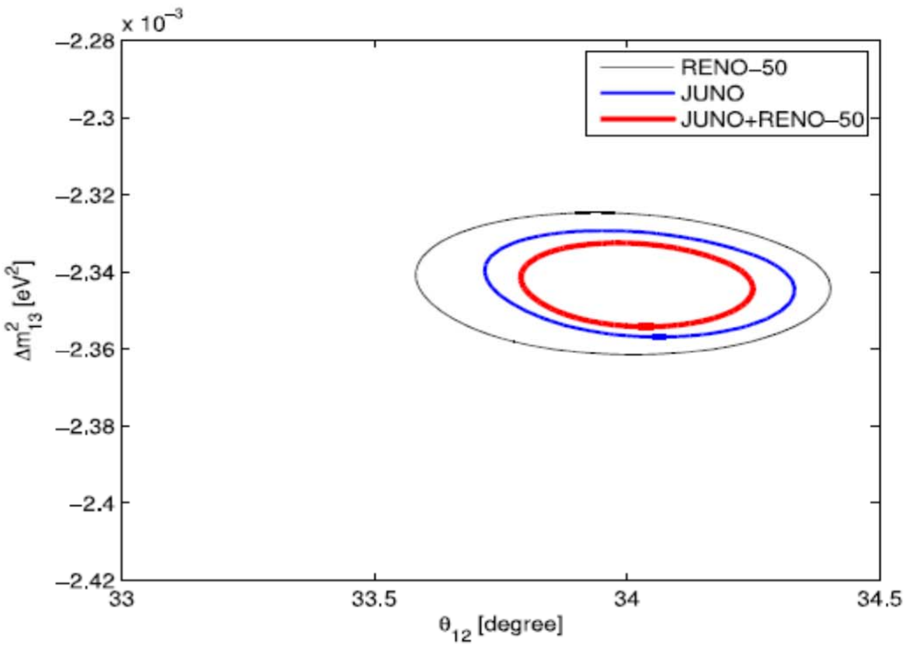
(d)


x 10^-3
2,48
2,46
2,44
2,42
2,4
2,38
2,36
33
33.5
34
34.5
RENO–50
Δm²_13 [eV²]
θ_12 [degree]

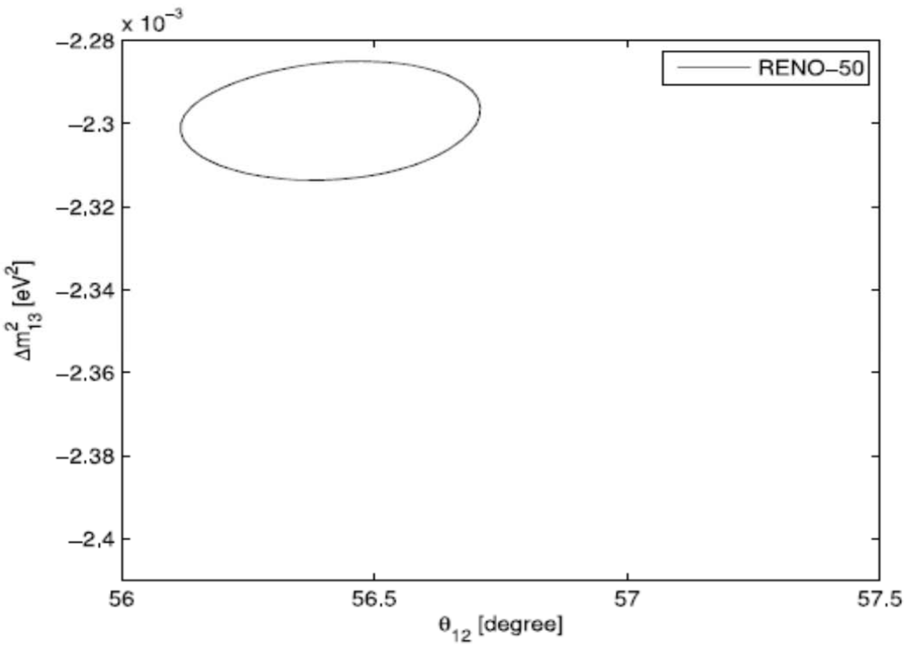
(a)


x 10^-3
2,48
2,46
2,44
2,42
2,4
2,38
2,36
56
56.5
57
57.5
RENO–50
JUNO
JUNO+RENO–50
Δm²_13 [eV²]
θ_12 [degree]

(b)


x 10^-3
–2,28
–2.3
–2,32
–2,34
–2,36
–2,38
–2.4
–2,42
33
33.5
34
34.5
RENO–50
JUNO
JUNO+RENO–50
Δm²_13 [eV²]
θ_12 [degree]

(c)


x 10^-3
–2,28
–2,3
–2,32
–2,34
–2,36
–2,38
–2,4
56
56.5
57
57.5
RENO–50
Δm²_13 [eV²]
θ_12 [degree]

(d)

Degeneracy

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left||U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}}\right|^2 = \left|c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}}\right|^2$$

$$s_{12} \leftrightarrow c_{12} \ (i.e.,\ \theta_{12} \to \frac{\pi}{2} - \theta_{12}) \quad \text{and} \quad \Delta_{31} \to -\Delta_{31} + \Delta_{21}$$

Degeneracy

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left||U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}}\right|^2 = \left|c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}}\right|^2$$

$$s_{12} \leftrightarrow c_{12}$$

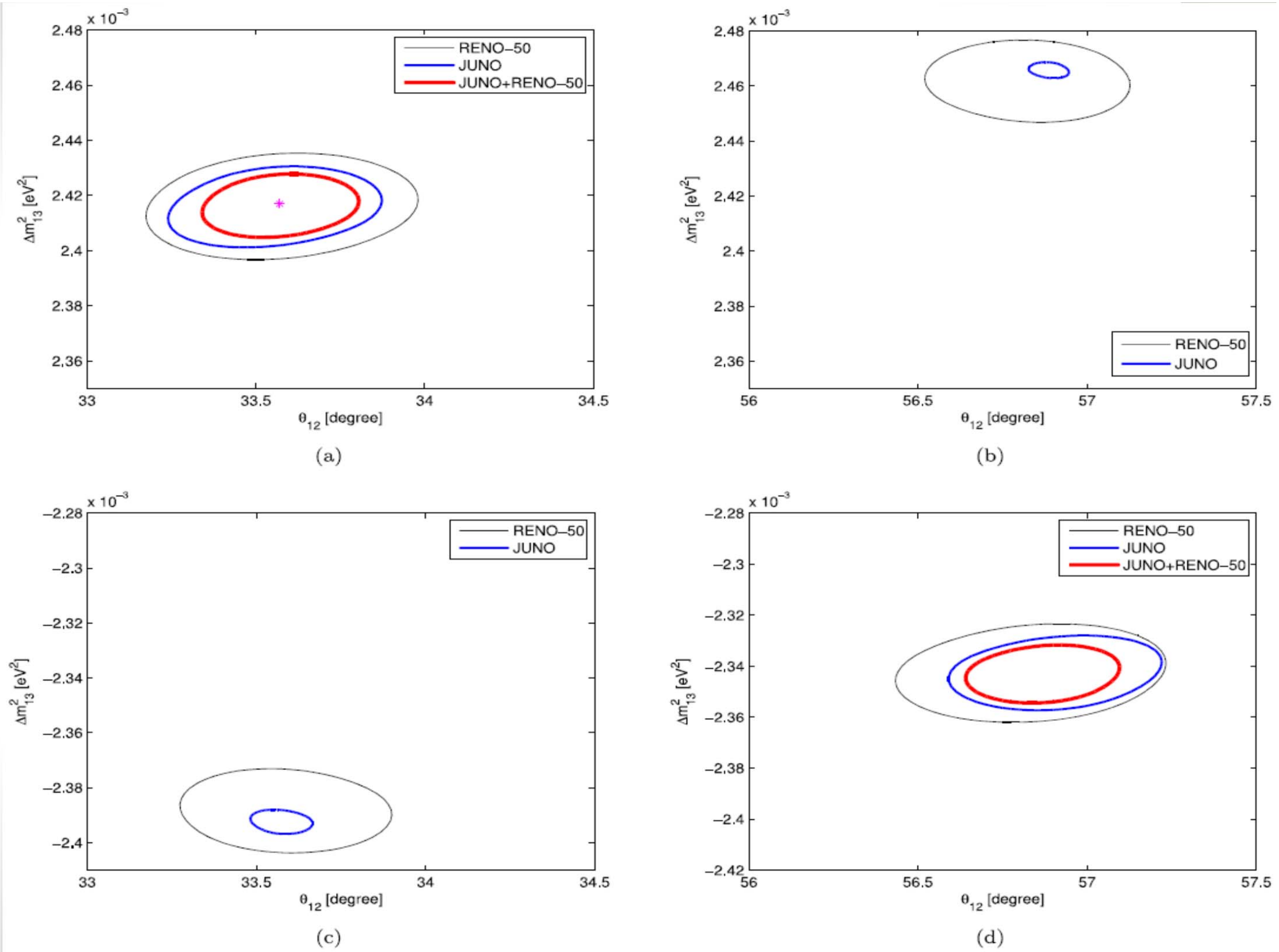
$$|s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}}| =$$

$$|s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{-i\Delta_{21}} + s_{13}^2 e^{-i\Delta_{31}}| =$$

$$|e^{i\Delta_{21}}(s_{12}^2 c_{13}^2 + c_{12}^2 c_{13}^2 e^{-i\Delta_{21}} + s_{13}^2 e^{-i\Delta_{31}})|$$

- As long as we neglect matter effects

$$s_{12} \leftrightarrow c_{12} \ (i.e., \ \theta_{12} \to \frac{\pi}{2} - \theta_{12}) \quad \text{and} \quad \Delta_{31} \to -\Delta_{31} + \Delta_{21}$$


x 10^-3
RENO−50
JUNO
JUNO+RENO−50
Δm^2_13 [eV^2]
θ_12 [degree]
(a)
(b)
(c)
(d)

Summary of results

- RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution

Summary of results

- RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution
  - Increasing energy resolution from 3% to 3.5% makes the wrong solution acceptable at 3 sigma!

Summary of results

- RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution
  - Increasing energy resolution from 3% to 3.5% makes the wrong solution acceptable at 3 sigma!
  - Removing the background, JUNO alone can rule the wrong solution at more than 3 sigma.

Summary of results

- RENO-50, JUNO and their combined data can discriminate between LMA and LMA-Dark, respectively at >90 % C.L., ~3 sigma C.L. and ~4 sigma C.L. after 5 years and with 3% energy resolution
  - Increasing energy resolution from 3% to 3.5% makes the wrong solution acceptable at 3 sigma!
  - Removing the background, JUNO alone can rule the wrong solution at more than 3 sigma.
  - There is a degeneracy that can be solved by oscillation experiments more sensitive to matter effects (like PINGU or INO investigating atmospheric neutrinos) or scattering experiments sensitive to NSI.

Backup

- Gadolinium-doped Liquid scintillator
- AD=anti-neutrino detector:
- Accidental background: correlation of two unrelated events

- Beta-neutron decay of Li/He produced by muons inside AD

- Neutron spallation

Solution of the puzzle

- Neutrino oscillation
- Potecorvo proposed in 1957 in analogy of

$$K^0 \leftrightarrows \bar{K}^0$$

Even before solar neutrinos were discovered!!!

Invisible Z decay width

$$Z \to e^- e^+ \quad Z \to \mu^- \mu^+$$

$$Z \to \nu_e \bar{\nu}_e, \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$$

Fourth Neutrino ?!